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TWO-PHOTON RERADIATION FROM LASER PROTECTIVE MATERIALS

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AUGUST 1978

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Several dyes used in laser protective devices were tested for reradiation in the 400 to 1000 nm wavelength region during and after irradiation by 17 nsec 1063 nm pulses of .23 ± .08 J. A statistical analysis led to the conclusion that, in both back and forward scattering directions, less than 2 x 10^6 photons were re-emitted in this wavelength region (with 99% confidence limit). These may thus be incorporated into a plastic host for use as eye protection and may be considered safe up to a radiation level which will damage the plastic host material itself.

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INTRODUCTION

Personnel in our laboratory have observed visible radiation apparently emanating from certain laser absorbing materials used in protective eyeware when these materials were illuminated with intense neodymium laser pulses at 1063 nm.

EXPERIMENTAL APPARATUS

The experiment was designed to minimize the possibility of detecting any scattered flash lamp light, laser rod fluorescence, or photons from any extraneous source. For this reason, the laser was located in a room adjacent to the specimen and detection apparatus. The connecting hole was covered by a bandpass filter. Reference to Figure 1 will indicate the general layout. Mirror M_1, which reflected only photons of wavelength 1063nm and eliminated photons at other wavelengths by transmission, and the bandpass filter F_1, which transmitted only the laser photons (at 1063nm) and blocked other wavelengths, both served to discriminate against unwanted photons. In addition, the laser-specimen distance of 10 meters minimized the effects of any off-axis photons generated by the flash lamp.

The photo diode detectors D_1 and D_2 served as shot-to-shot monitors of the pulse energy and duration. Detector D_2 was used to determine the characteristics of the pulse reaching the specimen, while comparison with D_1, which monitored the laser output more directly, served to indicate any deterioration of M_1 or F_1 or any wandering of the beam. The outputs of the detectors were displayed on a Tektronix model 556 oscilloscope. The detectors were calibrated by comparison with a thermopile, Quantronix model 504/501 (with specimen removed).

The beam reducing lenses L_1 and L_2 were used to increase the energy density of the pulse on the specimen. The limiting factor here was not related to the spectrometer slit size but was the damage threshold of the specimens. It was clear from photographic film exposed directly to the beam that there was considerable mode structure in the pulse and the energy density varied widely throughout the area of the beam cross-section.

Radiation from the specimen was gathered and focused onto the entrance slit of the spectrometer by lens L_3. Filter F_2, a multi-layer dielectric reflector, was identical to mirror M_1 and served to block diffusely-scattered 1063nm laser light. Additional IR or visible blocking filters were used as needed. A wide (1.5 mm) entrance slit was used on the spectrometer as detectivity, and not resolution, was to be maximized.

The spectrometer output window, with the exit slit removed, was coupled to a vidicon with an active area .5" wide. This vidicon served as the detector for the 500 channel analyzer. With the given linear dispersion at the exit slit of the spectrometer and the detector width, spectral ranges of ca. 160nm (1st order) and 80nm (2nd order) were covered for each setting of the spectrometer. Radiation throughout the visible region could, therefore, be detected with as few as four settings of the spectrometer, and the spectral window over which the Si vidicon detector is sensitive (ca. 350 - 1100nm) could be covered in its entirety with as few as five settings. In this experiment, spectrometer settings were chosen to give considerable overlap of spectral windows, generally as follows:

SPECTROMETER SETTING (nm)	RANGE 1ST ORDER (nm)	RANGE 2ND ORDER (nm)
700	620-780	310-390
800	720-880	360-440
900	820-980	410-490
1000	920-1080	460-540
1100	1020-1180	510-590
1200	1120-1280	560-640

It should be noted that a range in the visible of 80nm spread over 500 channels of detection would indicate a potential resolution of .16nm. However, due to the wide entrance slit used, obtainable resolution was about 5nm.

The silicon vidicon detector and multichannel analyzer functioned like a photographic-film/densitometer combination which could be exposed to one or more pulses and then read. It could also be read out in "real time" (32 msec delay). The vidicon/multichannel analyzer combination offered these advantages: the response of the silicon diode vidicon is higher than film, the IR response is more extensive, background can be subtracted, and "handling" is automatic.

The detector sensitive area was 12.7 x 5.1 mm or 500 times .001" by .2" (i.e., .5" x .2"). The analyzer scanned the 500 channels of the vidicon every 32 msec, extracting the data accumulated since the last scan. It then digitized the information and stored it, or added it to a memory. Note that although the data was scanned by the analyzer sequentially, it was accumulated in parallel (simultaneously) into the 500 channels, thus there is no lower limit on detectable pulse duration. However, two pulses less than 32 msec apart cannot be discriminated.

The analyzer had two memories. Immediately after a laser pulse irradiated a specimen, the target was scanned twice and the data (summed) put into the first memory. A single vidicon scan is not sufficient to read out all the light signal present on a target element. Measurements indicated that optimum signal-to-noise was achieved after read-out from two scans. After a pause of about 500 msec (during which any residual signal present was removed by scans which were not stored) the information from an identical pair of scans, but without a laser pulse, was put into the second memory of the analyzer. Using channel-by-channel subtraction, a background correction was effected which removed electronic offsets, residual dark current effects, and any constant stray light. The accumulated spectra differences were displayed on a CRT (signal minus background) and also transferred into a programable calculator, again channel-by-channel, for analysis.

The experiment was controlled by a Wang programable calculator, model 600-14, with appropriate interfaces to the multichannel analyzer, the laser, and the oscilloscope camera monitoring the detectors. The following sequence was followed:

charge laser flashlamp capacitors,
open oscilloscope camera shutter,
fire laser,
accumulate data into first memory
pause 500 msec,
accumulate background into second memory
close camera shutter,
transfer data to calculator,
analyze results.

If analysis indicated that another shot was necessary, the sequence was repeated after a pause of about 2 minutes (to allow the laser rod to cool sufficiently).

PERTINENT SPECIFICATIONS OF APPARATUS

Laser (L):	Korad Nd-glass model K-2:			
	pulse peak wavelength	1063	nm	
	pulse energy	~1.5	J	
	pulse half-width	~17	nsec	
	laser rod diameter	19	mm	(.75")
Detector (D_1):	Optics Technology model 620 photodiode rise time	<1	nsec	
Beam Splitter (BS_1):	glass slide			
Mirror (M_1):	Valpey multilayer dielectric reflector			
	central wavelength	1063	nm	
	peak OD	4.0		
	peak half-width	300	nm	
	luminous transmittance	90	%	
Filter (F_1):	Baird-Atomic bandpass filter type 36-14-6			
	central wavelength	1063	nm	
	peak transmittance	82	%	
	bandpass half-width	23	nm	
	upper blocking limit	X-ray		
	lower blocking limit	1200	nm	
	OD in blocking regions	>4		
Lenses (L_1) (L_2):	reducing telescope:			
	reduction	2:1		
Aperture (A):	metal plate:			
	diameter	13	mm	(.5")
	area	1.3	cm^2	
Beam splitter (BS_2):	National Photocolor Corp. uncoated pellicle			
reflection-transmission ratio		8:92		
Detector (D_2):	same as D_1			
Laser-specimen distance:		~10	m	
Lens (L_3):				
	f/ number	1.25		
	diameter	44	mm	
	focal length	55	mm	
	demagnification	2:1		

Specimen-spectrometer distance: 24 cm

Filter (F_2): same as mirror M_1

Spectrometer (S): EG&G 1/4 meter model 585-11 with 585-23 IR grating:

f/ number	6.6	
efficiency, avg. (2nd order)	30	%
image reduction	.56	
grating grove density	6.75	mm^{-1}
blaze wavelength	900	mm
reciprocal linear dispersion at exit slit (1st order)	12.8	nm/mm
range (1st order)	700-1600	nm
slit width	1.5	mm
slit height	4	mm

Multichannel analyzer/detector (MA): Princeton Applied Research OMA model 1205A/1205B:

Si target width	12.7	mm	(.5")
Si target height	5.1	mm	(.2")
spectral window	350-1100	nm	
sensitivity, average (see Figure 2)	5000	photons/count	
channels	500		
noise (single scan)	1.1	counts/channel	

Spectrometer-analyzer system:

spectral window (for given setting of spectrometer)		
(1st order)	165	nm
(2nd order)	82	nm
resolution (measured)	5	nm

Calibrating thermopile (TP): Quantronix Energy Meter, model 504/501

Additional filters:

Schott KG-3: infrared absorbing, visible transmitting.
Corning CS-1-59: visible absorbing infrared transmitting.

EXPERIMENTAL DESIGN

Preliminary data indicated that the experimental design need not center on analyzing apparent peaks, but on determining with what confidence it could be said that no peak was present.

Because of the large entrance slit used on the spectrometer (in comparison with the physical width of a channel of the detector), radiation of minimal spectral width would still be detected across about 30 channels. Therefore, an averaging algorithm for overlapping blocks of adjacent channels was used to eliminate any noise fluctuations which might be detected as peaks of less than w channels, with w an adjustable parameter. This averaging also increased detectability by reducing the noise (standard deviation) of points in the "averaged" spectrum. For each shot the total number of counts, z, in the averaged spectrum was determined and this was converted to the equivalent number of photons entering the spectrometer, p, by an experimentally determined conversion constant, g. This algorithm is as follows:

Consider M channels (counters) with outputs c_i and standard deviations $s_{n,i}$ from the i^{th} channel, the outputs being the difference (A-B) of a certain number of scans each in memory A and memory B, totaling n scans. Note that $s_{n,i} = n^{\frac{1}{2}} s_{1,i}$ where $s_{1,i}$ is the standard deviation from the i^{th} channel after one scan. Assume that in the absence of a signal the outputs are independent and each is normally distributed with a mean 0 and a variance $s_{n,i}^2$: $N(0,s_{n,i}^2)$. In the presence of a signal of r counts total assume v contiguous counters each add the signal r/v to their outputs (without additional noise) and are thus distributed: $N(r/v,s_{n,i}^2)$.

Consider a procedure for determining whether the null hypothesis, r = 0, is true or whether some alternative hypothesis, r = P, is true. We determine:

$$z = rw = \sum_{i=o}^{M-w} \sum_{j=o}^{wy} c_{i+j} = \sum_{i=y}^{wy} ic_i + w \sum_{i=1}^{M+2-2n} c_{w-1+i} + \sum_{i=1}^{w-1} (w-i)c_{M+1-w}. \quad (1)$$

For outputs consisting of dark current difference (noise) only, z is distributed normally: $N(0,s^2w^2(M-2w)+2s^2 \sum_{\hat{i}}^{w} i^2)$, assuming that all the $s_{n,i}$ are equal (=s). (Measurements confirm this assumption).

Now since $\sum_{\hat{i}}^{w} i^2 = w(w+1)(2w+1)/6$, the variance of z will be $w^2u^2s^2$, where $u^2 = M-w+1 - (w+w^{-1})/3$.

Thus in the absence of a signal z is distributed: $N(0,w^2u^2s^2)$; and in the presence of a signal z is also normally distributed: $N(rw,w^2u^2s^2)$.

However, the total counts under a peak, r, are proportional to the number of photons, p, entering the spectrometer; i.e., $p = gr$, defining g. From the definition of z, $p = gz/w$, and p is distributed $N(0,g^2u^2s^2)$ in the absence of a signal, and $N(gz/w, g^2u^2s^2)$ in the presence of a signal.

If no signal were present, the successive p_i measured would be due to noise effects only and would cluster about a value of 0, being arithmetically both positive and negative although the latter is physically meaningless in terms of photons. If there were a signal, buried in the noise, the various p_i would cluster about some non-zero value, say P. A standard sequential analysis procedure was adopted in order to determine whether the measurements p_i were members of the normal population with mean = 0 photons, or mean = P photons. The value P represents a "minimum detectable signal" and may be arbitrarily selected. However, the number of samplings, i.e., the number of laser shots, necessary to distinguish between 0 and P to a given level of significance goes as the inverse square of P and therefore, there are practical limitations to how small one may choose P to be. A discussion of the choice of P and of other parameters follows.

The parameters chosen or measured preliminary to the analysis were:

M = 500, the total number of sample points or channels;
n = 4, the number of scans making up a sampling;
w = 50, the number of adjacent points averaged to obtain smoothed spectrum;
$g = 2.7 \times 10^4$, the number of photons entering the spectrometer which will generate one count (measured);

s_1 = 1.1 counts/channel, the measured noise for one scan;

α = .01, the type I error tolerated (the probability that a signal will be falsely "seen" when none exists);

β = .01, the type II error tolerated (the probability of falsely identifying a real signal as none (i.e., noise)); and

P = 2×10^6 photons, the chosen "minimum detectable signal".

M: The number of sample channels was set at 500 by the design of the optical multichannel analyzer.

n: As mentioned in the last section, an experimental determination of the signal-to-noise ratio as a function of number of read-out scans indicated that the optimum was two scans. The measured signal approaches the "real" signal with increasing number of readout scans since only a fraction of counts is transferred in a single scan. However, the signal must be considered as a function of the number of pairs of scans, one with signal and one without (i.e., A-B), as this is the way the instrument operates. The signal increases as:

$$S\left[1-(1-f)^i\right] \tag{2}$$

where S is the signal,

f is the fraction of counts transferred in a single scan, and

i is the number of pairs of scans.

The noise increases as $s_1(2i)^{\frac{1}{2}}$ with each pair of scans (s_1 is the noise in a single scan), and therefore the signal-to-noise ratio (SNR) is:

$$SNR = 2^{-\frac{1}{2}} S s_1^{-1} i^{-\frac{1}{2}} \left[1-(1-f)^i\right] \tag{3}$$

The optimum number of scans, to maximize the SNR, depends only on i and f.

For f = .50 (measured), we have:

i:	1	2	3
$i^{-\frac{1}{2}}\left[1-(1-f)^i\right]$:	.50	.53	.51

(4)

with a clear maximum at 2 scan-pairs, or 4 scans total.

w: The parameter w, the expected minimum signal width (spectral width expressed in number of channels), was chosen arbitrarily based on the 30 channel width of a narrow spectral source (laser). Preliminary calculations made with w varying between 1 and 150 channels showed no change in experimental results.

g: This parameter, the photons at the entrance slit of the spectrometer necessary to produce one count in the analyzer, is the product of an average vidicon response estimated from the vidicon response curve (see figure 2) and the estimated average efficiency of the spectrometer. The former was experimentally confirmed at a wavelength of 632.8 nm for this particular vidicon, using a He-Ne laser with a calibrated output. The spectrometer efficiency estimation (second order) was also based on measurements at 632.8 nm.

s_1: This parameter, the standard deviation of the output from a single channel for one scan, was measured for several individual channels, both in the presence of a constant signal and without a signal. More extensive measurements were made of the average s_1 of the 500 channels. Measurements in the absence of a signal, made by covering the vidicon faceplate, determine the system noise per channel per root scan. The results validated the assumptions made in the experimental design, that is, that $s_{1,i}$ was the same for all channels either in the absence or the presence of a (constant) signal. The noise was reduced to a value of 1.10 counts per channel per root scan after several modifications to the instrument. (A subsequent modification, made after the experimental data was taken, lowered this figure to .80 counts per channel per root scan.)

Clearly, even in the absence of a light signal into the vidicon, and making allowances for the tube "dark current", the number of counts (the input) in any given channel might still be non-zero because of noise, However, the signal averaged over many trials should approach zero, and the average over all 500 channels of a single scan should approach zero as well. The former hypothesis was found to be true, but tests on the latter showed that intermittently the average signal over all 500 channels was "elevated", fairly uniformly, and could be as many as ± 30 standard deviations from zero. The source of this intermittent spurious signal was traced to the vidicon itself, as opposed to some problem in the analyzer, but we were unable to eliminate it. A second vidicon was obtained from the manufacturer but it has the same intermittent problem, which appears to be inherent in the design of the tube itself. At present we are working with the manufacturer to locate the source of this problem and eliminate it.

α, β : The type I and type II errors to be tolerated were each set arbitrarily at the 1% level so that the acceptance or rejection of the hypothesis that the p_i came from one population or the other may be considered highly significant.

P : Using a faint narrow band light source (a He-Ne laser with neutral density filters), an estimation of the minimum visually detectable signal was made. The determination was made by irradiating

the spectrometer-detector system, accumulating into one memory for two scans, and then subtracting two scans of background from the second memory. In this way the estimation was made under the same noise conditions as the experiment, i.e., two scans of signal less two scans of background without signal. The signal was spread over approximately 30 channels because of the spectrometer slit width. The minimum visually detectable signal was about 90 counts or about 3 counts per channel. This included a noise of $s_{4,i} = n^{\frac{1}{2}} s_{1,i} = 2.2$ counts per channel, or a signal-to-noise ratio of ca. 0.4. The 90 counts corresponded to 4.5×10^5 photons into the detector and about 1.5×10^6 photons into the spectrometer.

In a sequential analysis procedure the number of test (p_i) determinations one can expect to make before a decision is reached can be calculated for various true situations. The expected average sample number reaches a maximum for the situation where the "true" value is midway between the two means assumed for the test, in this case $\frac{1}{2}P$ (midway between 0 and P). If the type I and II errors are taken to be equal ($\alpha = \beta$) and the standard deviation of p is s_p ($=n^{\frac{1}{2}}s_1 ug$ in this case), the expected average sample numbers for a "true" value midway between the two means of the test and for "true" values at either of the two means assumed (0 or P) are, respectively: (ref. 1):

$$s_p{}^2 P^{-2} \ln(\alpha^{-1}(1-\alpha)) \quad \text{and} \quad 2s_p{}^2 P^{-2}(1-2\alpha)\ln(\alpha^{-1}(1-\alpha))$$

For $\alpha = \beta = .01$, and $s_p = 1.23 \times 10^6$ (which follows from the assumptions made for n, s_1, g, M, and w), the expected average sample number (laser shots) necessary to reach a decision will be as follows:

"true" value:	0 or P	$\frac{1}{2}P$
$P = 2 \times 10^6$:	3.4	8.0
$P = 1 \times 10^6$:	13.6	31.9

(5)

Using these figures and the minimum visually detectable signal as guidance, the minimum detectable signal chosen for the algorithm was $P = 2 \times 10^6$ photons. Note that this signal may be as narrow as 30 channels or may be spread out over all 500 channels and still be "detected" by the calculation although, of course, visual identification of a peak of 90 integrated counts becomes progressively more difficult as the peak width increases.

(The average sample number found was 4.3)

The analysis procedure is as follows:

1. set parameters
2. calculate $\ln \alpha^{-1}(1-\alpha)$ (used in sequential analysis comparisons)
3. calculate $u = M-w+1-(w+w^{-1})/3$
4. calculate $s_p = n^{\frac{1}{2}}gus_1$
5. fire laser
6. accumulate data (signal less background in each channel)
7. transfer the c_i to calculator
8. calculate z
9. calculate, print $p = gw^{-1}z$ = number of photons entering spectrometer
10. calculate test function $T_m = Ps_p^{-2} \sum_0^M P_i - \frac{1}{2}P^2 s_p^{-2} m$ from the accumulated p's
11. test: if $T_m \leq \ln \alpha^{-1}(1-\alpha)$ accumulate additional data (i.e., return to step #5. If $T_m > \ln \alpha^{-1}(1-\alpha)$ print 0 or P as appropriate. Accept (or reject) the null hypothesis at the 1% level.

SAMPLES TESTED

The following dyes, all from American Cyanamid, were tested for two photon reradiation:

1. TEAAF (H-99) in cellulose propionate
   O.D. at 1063 nm = 17.0
2. TEAAF (H-99)
   O.D. at 1063 nm = 10.0

3. TBAAF (IR 282) and K283 in an Air Force visor (PMMA)
   O.D. at 1063 nm = 4.2
4. 5H-6M-BP nickel in acetone (1 cm cell)

O.D. at	before test:	after test:
1060 nm	1.8	1.1
530 nm	.85	.57

Abbreviations are as follows:

TEAAF: tris (p-diethylaminophenyl) ammonium hexaflouroantimonate

TBAAF: tris (p-dibutylaminophenyl) ammonium hexaflouroantimonate

5H-6M-BP nickel: bis (hydroxy-6-mercapto) benzo(C) phenanthrene nickel

TEAAF, a 1.06 & .69 um absorber, was tested because of reported two-photon reradiation.

TBAAF, also a 1.06 absorber, is currently used with a .53 um absorber (K283) in Air Force laser protection goggles. 5H-6M-BP nickel was tested because it was thought to have potential for strong two-photon effects.

RESULTS

The table below gives the results for the four specimens studied. Backward scattering runs were made with the spectrometer-detector 48° off axis and forward scattering with it 20° off axis. The number of shots column refers to the sequential analysis procedure and gives the number of trials necessary to achieve a result at the 1% confidence level. The average number of shots was 4.3, to be compared with an expected average of 3.4 if the "true" value of P were zero.

The table shows only the spectrometer setting. The corresponding spectral ranges covered may be determined from the table on page 2. The total spectral range reported for each specimen should be considered to be 400 to 1000 nm. In some cases small peaks were detected by the OMA at wavelengths longer than 1060 nm. These were eliminated using a Corning 1-59 (IR absorbing) filter in front of the spectrometer.

Over the course of the experiment the beam energy hitting the various specimens varied from a low of .15 J to a high of .30 J. There were variations from shot to shot but the factor of 2

variation occurred slowly (downward) during the course of the experiment. This was due to various factors including deteriorations of the filter F_2 and problems with the laser rod. The pulse was spread over a circular area of 1 cm diameter, with considerable energy non-uniformity across the beam. Only the roughly central .12 cm^2 was imaged on the spectrometer slit however, and since this portion of the beam was more intense, the energy densities reported are very conservative. Both the average energy density per shot and average energy per shot are reported below.

SPECIMEN	SCATTERING DIRECTION	SPECTROMETER SETTING (nm)	NUMBER OF SHOTS	AVG ENERGY DENSITY/SHOT (J/cm^2)	AVG ENERGY PER SHOT (J)	RESULT
1	back	1200	3	.21	.025	null
		1100	3	.22	.027	null
		1060	3	.22	.026	null
		1000	5	.18	.022	null
		900	3	.19	.023	null
		800	6	.20	.024	null
		700	3	.20	.024	null
1	fwd	1300	2	.15	.018	null
		1200	10	.16	.019	null
		1150	4	.16	.019	null
		1060	11	.15	.018	null
		950	3	.15	.018	null
		850	6	.14	.017	null
		750	2	.14	.017	null
2	back	1300	2	.14	.017	null
		1200	3	.15	.017	null
		1100	3	.14	.017	null
		1060	3	.14	.016	null
		950	5	.15	.018	null
		850	4	.15	.018	null
		750	7	.15	.018	null
2	fwd	1300	5	.14	.017	null
		1200	7	.14	.017	null
		1150	2	.13	.015	null
		1060	8	.14	.017	null
		950	2	.13	.016	null
		850	4	.14	.016	null
		750	6	.13	.016	null

SPECIMEN	SCATTERING DIRECTION	SPECTROMETER SETTING	NUMBER OF SHOTS	AVG ENERGY DENSITY/SHOT (J/cm^2)	AVG ENERGY PER SHOT (J)	RESULT
3	back	1300	5	.13	.015	null
		1200	8	.13	.015	null
		1150	3	.13	.016	null
		1060	6	.13	.016	null
		950	2	.13	.016	null
		850	3	.13	.016	null
		750	6	.13	.016	null
3	fwd	1300	4	.14	.017	null
		1200	4	.14	.017	null
		1150	3	.14	.017	null
		1060	3	.14	.016	null
		950	5	.13	.016	null
		850	4	.14	.016	null
		750	4	.14	.017	null
4	90°	1300	2	.16	.019	null
		1200	5	.16	.019	null
		1100	4	.14	.017	null
		1060	4	.16	.019	null
		950	2	.15	.018	null
		850	4	.16	.019	null
		750	9	.14	.017	null

Since all the specimens gave null results, a brief test was made of the total experimental arrangement while in the forward scattering configuration. A piece of plastic coated with rhodamine 6G was irradiated. Reradiation in the vicinity of 530 nm from one laser shot was sufficient to drive the optical analyzer off-scale.

The standard deviation of all the experimentally determined p's (number of photons entering the spectrometer) was $s_p = 1.26 \times 10^6$ photons. This compares well with the calculated value of $s_p = 1.23 \times 10^6$ photons calculated from the assumptions made for n, s_1, g, M, and w).

CONCLUSION

In summary, for all samples in both back and forward scattering positions, we can say with 99% confidence that less than 2×10^6 photons of wavelength 400 to 1000 nm were emitted from the central irradiated area with laser radiation levels not far below that necessary to damage the plastic.

While 2×10^6 may seem like a large number of photons (for those accustomed to photon counting), it is orders of magnitude below any danger level. In fact, in the green, 2×10^6 photons/sec corresponds to 8×10^{-13}W or 4.9×10^{-10} lumens. (Starlight illumination is about 10^{-3} lumens/m^2). However, in future experiments it is expected that P, the minimum detectable number of photons, will be lowered by the development of a more sensitive algorithm for peak detection.

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1. Wilfred J. Dixon and Frank J. Massey, Jr., Introduction to Statistical Analysis, McGraw-Hill Book Company, Inc., New York, NY, 1957, 2nd edition.

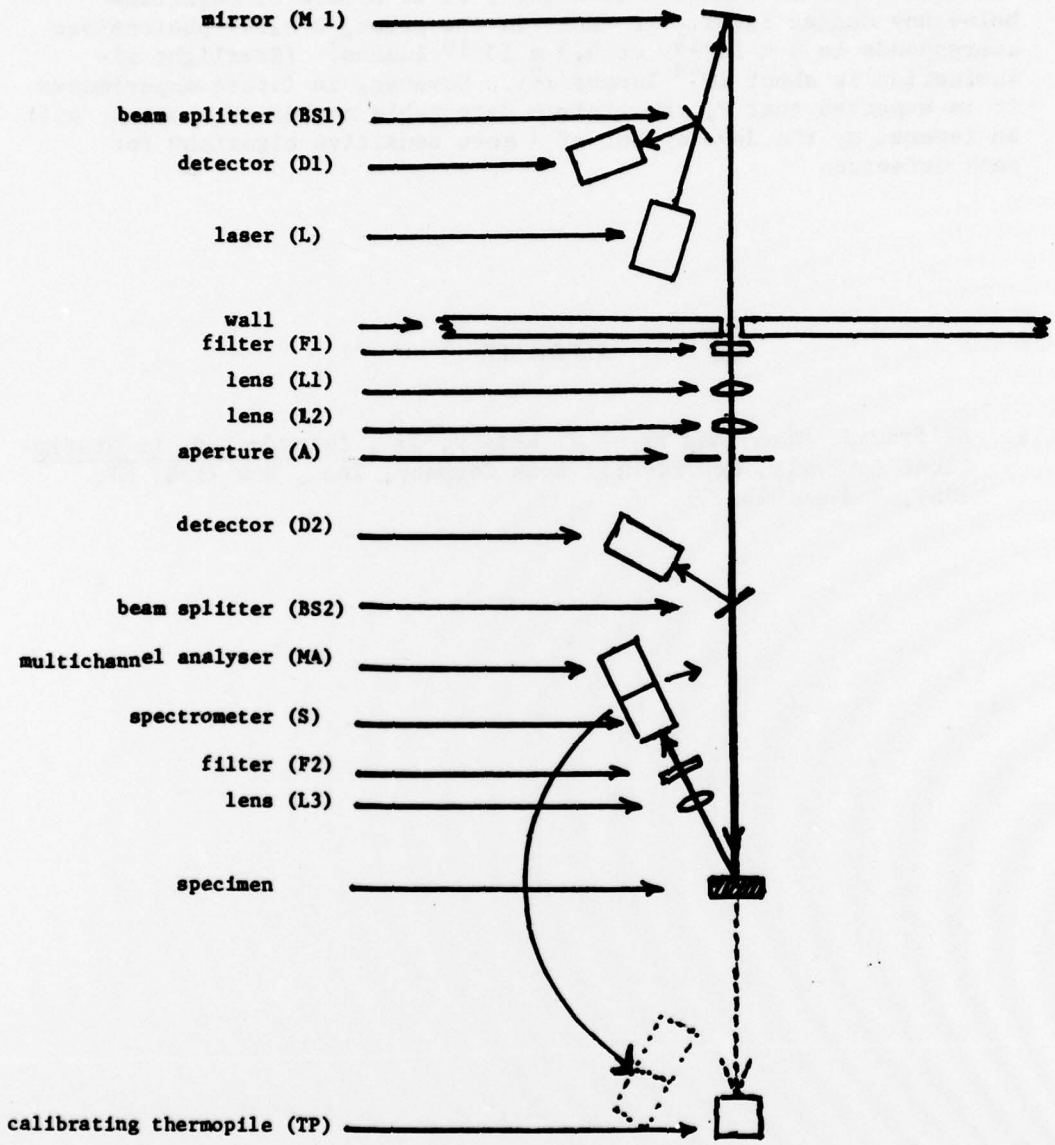

Figure 1. Experimental apparatus.

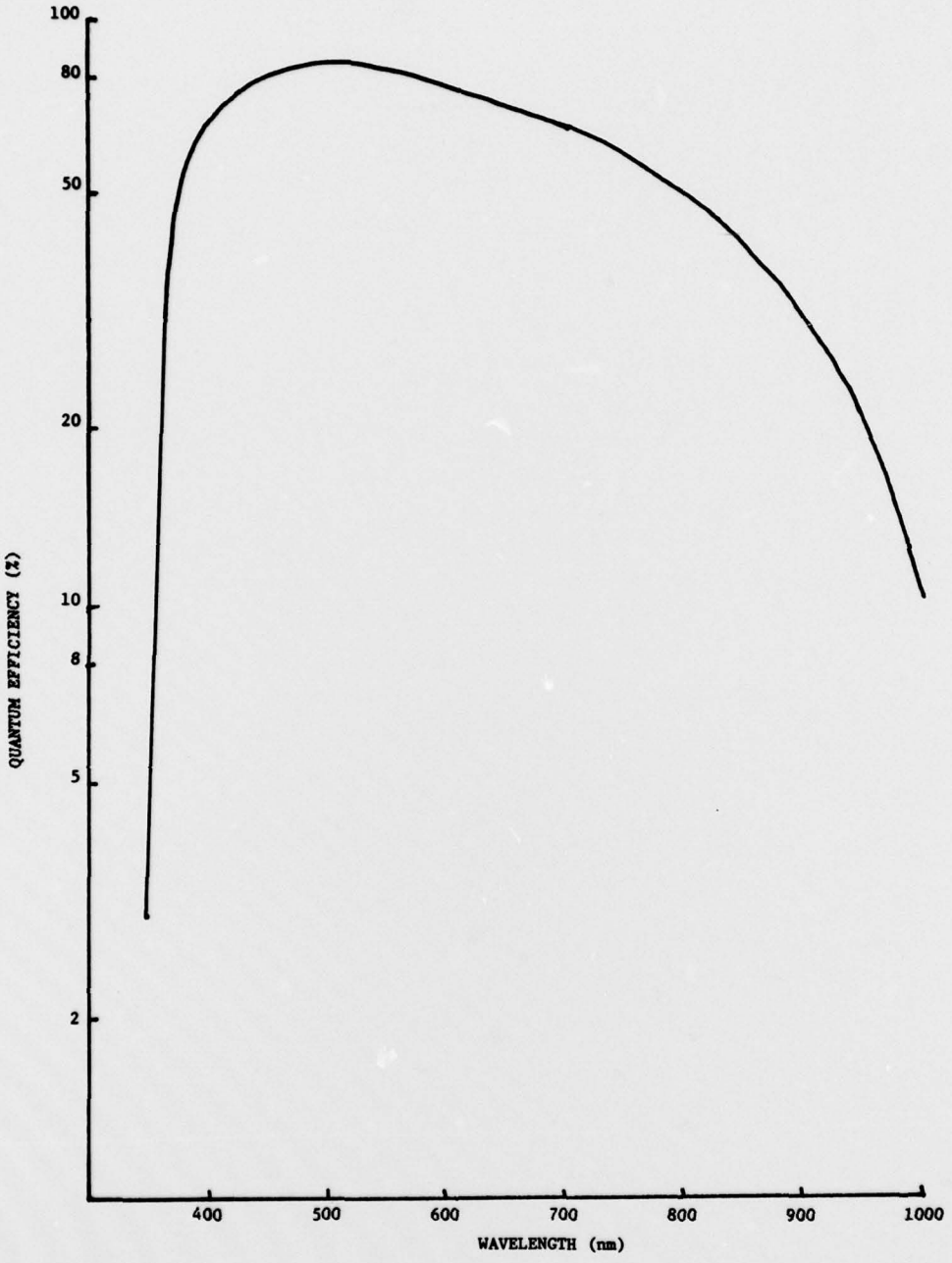

Figure 2. Detector spectral response.

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